Update on the SKA Offset Optics Design for the U.S. Technology Development Project

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Abstract— The U.S. design concept for the Square Kilometre Array (SKA) program is based on utilizing a large number of small-diameter dish antennas in the 12 to 15 meter diameter range. [1][2]The Technology Development Project (TDP) is planning to design and build the first of these antennas to provide a demonstration of the technology and a solid base on which to estimate costs. The latest considerations for selecting both the optics and feed design are presented.

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1. INTRODUCTION

The U.S. design concept for the Square Kilometer Array (SKA) program is based on utilizing a large number of small-diameter dish antennas in the 12 to 15 meter diameter range. The Technology Development Project (TDP) is planning to design and build the first of these antennas to provide a demonstration of the technology and a solid base on which to estimate costs. This paper is an update to [1] and the latest considerations for selecting both the optics and feed design are presented including the efficiency and noise temperature performance.

The reasons for choosing dual, shaped offset reflectors for the SKA / TDP antennas can be grouped into scientific, financial, technical categories. The scientific requirements for these antennas are stringent. They must have low noise, high efficiency, very low wide angle scattering (sidelobes), accurate and stable pointing, all at an affordable total system cost. The offset optics provides a clear optical path and aperture which does not scatter any radiation out of the focused region.

Combined with low illumination at the edges of the two reflectors, this can lead to very low sidelobes away from the main beam and its first few sidelobes. Dual reflector shaping is used to provide high aperture efficiency with low edge illuminations. The very small wide angle sidelobes from a good offset design reduce the received levels of strong sources out of the field of view, enhancing high dynamic range, a key scientific requirement. They also provide enhanced rejection of RFI, especially from satellites.

There is also the need for very wide bandwidth feeds. The requirement is for the SKA to cover the 0.3 to 10 GHz frequency bands. There are four feed types currently under consideration; the Quasi Self-complementary (QSC) feed developed by G. Cortes of Cornel [2], the Log periodic dipole antenna developed for the Allen Telescope Array (ATA) project [3], a Quad-ridged feed improving the design of the similar type feed from the Lindgren company utilized on the Goldstone Apple Valley Radio Telescope (GAVRT) project [4] and the Eleven feed developed by P. Kildal [5].

Key performance parameters include both the efficiency and noise temperature as a function of frequency in order to evaluate A/Tsys for each feed type.

2. WHY AN OFFSET SHAPED DESIGN

At first glance, rotationally symmetric antennas and offset antennas look very different. However, many of the subsystems in each are very similar or at least analogous. The mount is the most obvious example of this. It is virtually the same regardless of what type of antenna it supports. Comparative study of subsystems leads to the conclusion that there is not a large cost difference between the two types. Such a comparative study was done during the early design stages of the Green Bank Telescope (GBT). The differential in that case was estimated at about 1.25 [6]. That differential included the cost of making one-off asymmetric panels and an entire substructure to transfer the panel attachments to the main load bearing structure. The

[1] 978-1-4244-7351-9/11/$26.00 ©2011 IEEE
[2] IEEEAC paper#1597, Version 2, Updated 2011:01:12

SKA antennas will most likely be single piece reflectors so once the required molds are made there is essentially no premium for asymmetric reflectors. Given the modest increment in cost and a significant improvement in performance, the total system cost might well be less with offset antennas even though their unit cost is somewhat higher.

3. Feeds under consideration

As stated earlier, there are 4 wideband feed types under consideration, for the SKA-TDP:

- The Lindgren feed [4], which is a commercial open boundary Quad-Ridged Horn sold by ETS-Lindgren. We have measured data patterns for one of these feeds inside of a cryostat from 2 to 19 GHz, although the input match is only appropriate for 5:1 band ratio.
- The QSC feed [2], is an ultra-wide band feed that has a measured input match better that -10 dB over 10:1 bandwidth. There are three versions being considered for the optics design: the first one is based on measured data from an actual QSC prototype that operates from 0.4 to 4.0 GHz, the second, QSC in a can, is based on calculated pattern data of a QSC model inside of a metallic cylinder, the presence of the wall of the can actually improves the directivity without compromising the input match. The third is the QSC-i, a new and improved version of the QSC feed that is intended to operate from 1 to 10 GHz, for this there are calculated patterns.
- The ATA feed [3] is an ultra-wide band log-periodic feed developed for the Allen Telescope Array. The ATA feed has frequency coverage in excess of 15:1, with good match over the band. There are both simulated and measured antenna patterns.
- The Eleven feed [5] is a compact feed based on a parallel folded dipole configuration over a ground plane, with frequency coverage of 10:1. At this time the data for the Eleven feed is not available to be presented, but the feed will be considered as a possible candidate.

Figures 1 through 3 show the calculated Directivity, Cross-polarization and the half beam size, at the -10dB level, as a function of normalized frequency for several of the feeds.

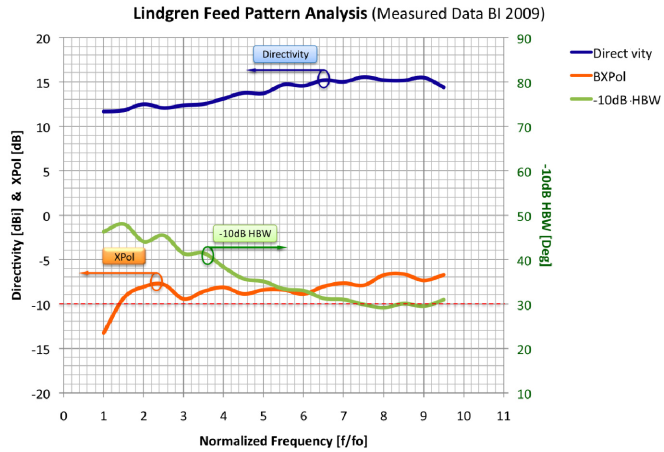

Figure 1. Directivity, Cross-Pol and -10 dB HBW vs. normalized frequency from measured (2 to 19 GHz) Lindgren feed radiation pattern.

In Fig. 1, the directivity of Lindgren feed is shown, which varies approximately linearly from 11.7 dBi, at f/fo=1, to 15.1 dBi at f/fo = 6, and it maintains this level up to f =9 fo. On the other hand the -10 dB Half Beam Width angle varies from 46° at f=fo and decreases to approximately 30° at the upper edge of the band. This has implications in the optics design, as the appropriate illumination angle should be selected at some intermediate frequency to properly balance the over-illumination at low frequencies (higher noise temperatures due to spillover) with the under-illumination at high frequencies. Finally, the orange curve at the bottom of Figure 1 shows the integrated cross-polarization inside the -10 dB beamwidth for the Lindgren feed. The cross-polarization is very high, mostly above -10 dB, and as much as -6.7 dB in the high-end of the band. The reason for this is that the quad-ridge configuration of the Lindgren feed uses Vivaldi (exponentially taper) elements as radiators, which inherently yield high cross-polarization.

Fig. 2 shows the calculated directivity, -10dB HBW and cross-polarization for the QSC-I feed. The feed directivity is fairly constant and above 10dBi for most of the band, including the low frequency. The beam size is smaller, about 57°, and has very little variation when compared with the other QSC feeds. The cross-polarization is better than -10 dB over the band.

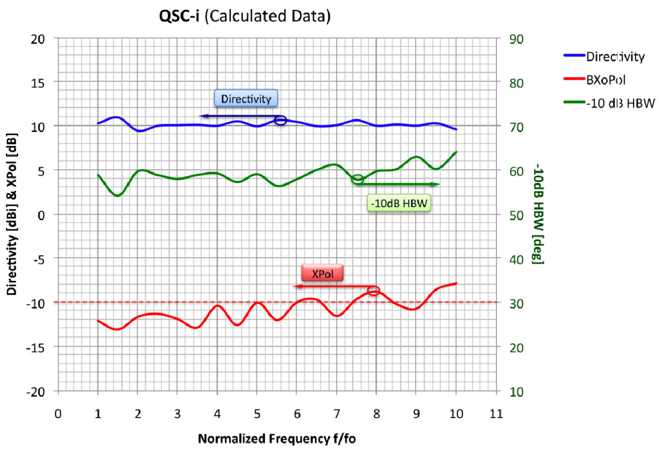

Figure 2. Calculated Directivity, Cross-Pol (left axis) and -10 dB HBW (right axis) vs. normalized frequency for the QSC-i feed.

Figure 3 shows the calculated directivity, -10dB HBW and cross-polarization for the ATA feed. The feed directivity is constant and about 12dBi for most of the band, except at the low frequency end. The -10dB HBW beam size is 42° in average, and has very little variation. The cross-polarization is better than -10 dB for most of the band.

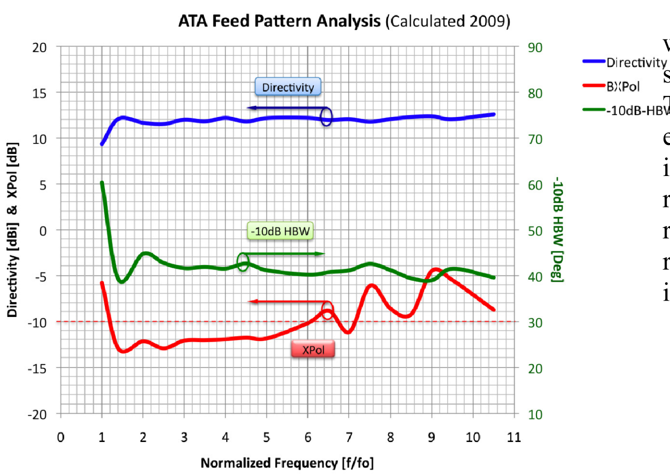

Figure 3. Calculated Directivity, Cross-Pol (left axis) and -10 dB HBW (right axis) vs. normalized frequency from ATA feed.

4. DUAL REFLECTOR SHAPING

Dual reflector shaping is utilized to both increase the aperture efficiency and reduce the noise temperature. The aperture efficiency is increased by making the aperture illumination more uniform. Noise temperature is decreased capturing more of the feed energy in the subreflector and thus by reducing the amount of energy that is spilled past the subreflector.

The reflectors are designed with a shaping method that controls the how the energy from the feed is distributed across the aperture plane. In particular, a deeply tapered feed illumination can be redistributed to a more uniform aperture illumination with a steep roll off near the aperture edge. This raises the spillover efficiency of the system by capturing more of the energy from the feed and keeps the aperture efficiency high by controlling the aperture distribution without raising the spillover past the primary edge.

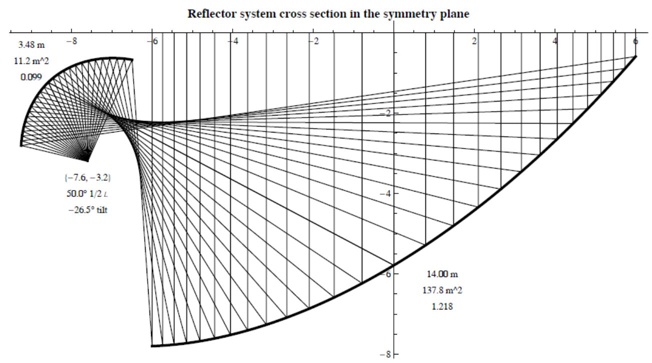

Figure 4. Reflector system cross section in the symmetry plane

Fig. 4 shows a cross section of a typical offset system with a 12 meter aperture in the plane of symmetry. The shaping is evident in the ray distribution in the aperture. The plotted rays emanate from the focus with equal steps in elevation angle and map to the aperture plane with large increments in radius in the center and small increments in radius near the edge. This gives the desired energy redistribution. One side effect of the shaping is obvious; the rays do not cross at an intermediate focus but are spread out in a caustic region.

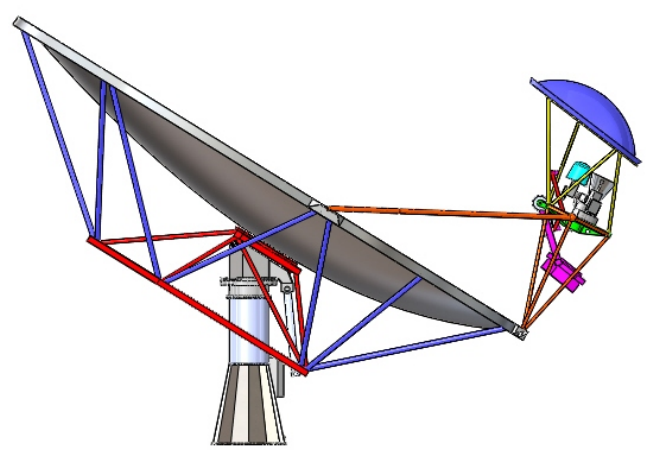

Figure 5. Drawing of antenna showing feed indexer

Various parameters of this optical system are shown on the plot. The location of the focus, the half angle subtended by the edge of the secondary and the tilt angle of the boresite ray are shown under the focal point. The rim to rim dimension, total reflector area and the area as a fraction of the aperture disk are shown close to each of the reflectors. Although the secondary looms large in this view, it is less than 1/12 of the size of the primary in area. A 3-dimensional drawing of the antenna is shown in Fig. 5. The critical parameter in the design is the half-angle subtended by the secondary. Since each feed has a different gain and half-power beamwidth a different subreflector half-angle is required for maximum efficiency over the frequency band. This is illustrated in figs 6 and 7 where the efficiency versus frequency in a 12-meter antenna of the ATA and QSC_i feeds are shown for various subreflector half-angles. Observe that a half angle of 45 degrees is optimum for the ATA feed whereas a 65 degree half-angle is optimum for the QSC_i feed.

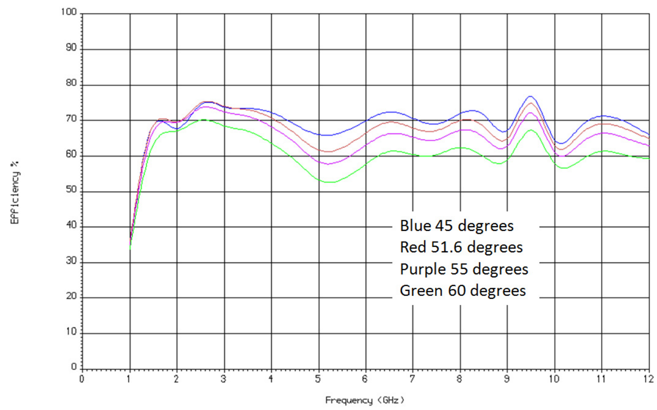

Figure 6. ATA Calculated Feed (Efficiency in a 12-meter antenna)

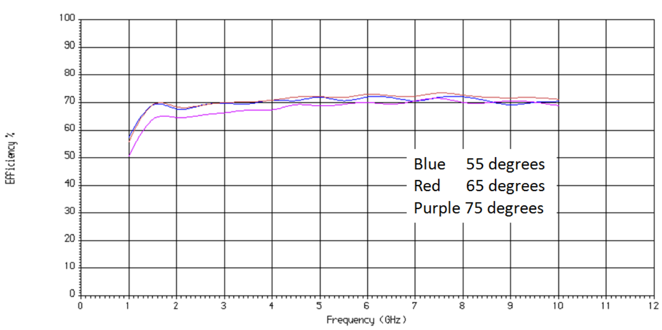

Figure 7. QSC_i Calculated Feed (Efficiency in a 12-meter antenna)

5. Noise Temperature

The antenna noise temperature is an important part of the overall system temperature T_{SYS}, given by,

$$T_{SYS} \quad = \quad \eta_L \, T_A + (1 - \eta_L) \, T_p + T_{REC} \tag{1}$$

Where, η_L is antenna ohmic losses, T_A is the antenna noise temperature, T_P is the antenna physical temperature, and T_{REC} is the receiver temperature.

The antenna temperature is given by [7],

$$T_A(\nu\,|\hat{\mathbf{r}}_o) \quad = \quad \frac{\displaystyle\iint_{4\pi} T_b(\nu,\theta,\phi)\, P_n(\nu,\theta,\phi\,|\hat{\mathbf{r}}_o)\, \sin\theta\, d\theta\, d\phi}{\displaystyle\iint_{4\pi} P_n(\nu,\theta,\phi)\, \sin\theta\, d\theta\, d\phi} \tag{2}$$

Where, $Pn(\nu, \theta, \varphi \mid \mathbf{ro})$ is the total (Co-polar + Cross-Polar) radiation pattern of the antenna, at the frequency ν, and direction (θ, φ), when the antenna main beam is pointing in the direction **ro**, see Fig. 8. $Tb(\nu, \theta, \varphi)$ is the *apparent radiometric temperature* also known as the *brightness temperature distribution* surrounding the antenna at that particular frequency.

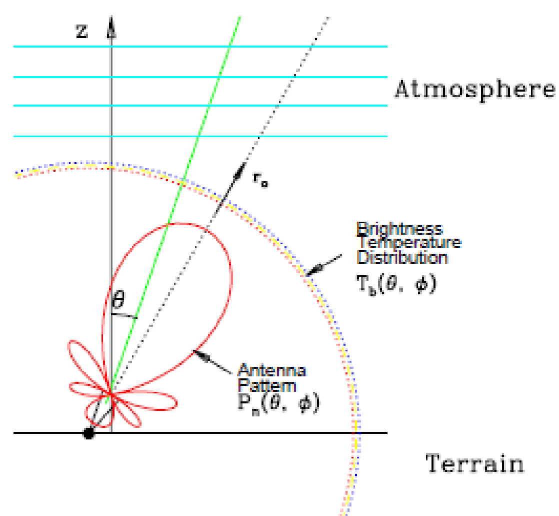

Figure 8: Relation between antenna temperature, antenna radiation pattern and the brightness temperature of the observed scene

The brightness temperature has different contributions: the cosmic emission, that includes the *cosmic microwave background* emission, 2.73K, galactic emission, (mostly synchrotron), which is of the form,

$$T_{gal}(\nu) \quad = \quad T_{g_o} \left(\frac{\nu_o}{\nu}\right)^{\beta} \tag{3}$$

With νo = 408 MHz, and β, the spectral index. There is also an atmospheric emission and ground reflection and emission. A detail account of all these contribution can be found in [7]. An important point is that we need the full antenna pattern, which is costly computationally, to calculate the antenna noise temperature.

Far Field Radiation Pattern Characteristics of a Dual Offset Gregorian Antenna

The Aeff is just one component of the optimization of Aeff/Tsys. Equally important it is the proper quantification of the antenna noise temperature component of Tsys.

Fig. 9 shows the main diffraction components of the full radiation pattern of an offset Gregorian reflector optics design. Most of the energy goes to the main beam, but also there are two diffraction cones produced by spillover past the sub-reflector and the main reflector respectively.

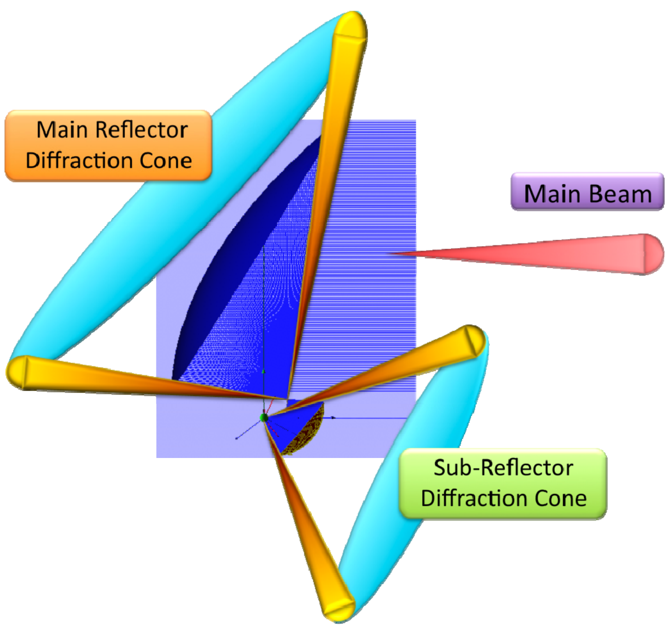

Figure 9 Main diffraction components of full radiation pattern in an Offset Gregorian Optics

The sub-reflector diffraction cone is produced by the diffraction of feed illumination at the sub-reflector's edge. The vertex of this diffraction cone is at the secondary focus, and its direction coincides with the feed orientation. Dependent on the particular design illumination angle, the upper portion of the sub-reflector diffraction cone radiates at a direction approximately 30° (in Figure 9) above the main beam, so it normally points to the sky. This diffraction beam sits between the main beam and the upper diffraction cone of upper section of the main reflector. The lower portion of the sub-reflector diffraction cone points normally towards the ground, and it will cause an increase in noise temperature. This is the situation with the sub-reflector and feed located in the lower position of the optics. In the upper position, the power impinging on the sky and ground is reversed, i.e., the power directed to the sky (ground) with the feed arm down is directed to the ground (sky) with the feed arm in the upper position.

The main reflector diffraction cone vertex is centered at the system prime focus. The upper portion of the diffraction cone points normally towards the sky, with the feed arm in the lower position, and it will point to the ground with the feed arm in the upper position. The lower portion of the main reflector diffraction cone points mostly to the back (and hence to the ground), and regardless of the feed arm location, up or down, will contribute to increase antenna noise temperature.

Approximate Noise Temperature Computations

In order to properly tradeoff the various antenna and feed configurations for the SKA optical design it is necessary to evaluate the gain and noise temperature of each configuration over a wide range of frequencies. The standard technique for calculating noise temperature is detailed above. However, since the total antenna pattern needs to be calculated over the entire 4 pi steradians at a fine enough resolution to accurately include the main beam, the computer time required is enormous. Even at modest frequencies and reflector sizes (~5 to 10 GHz for a 12 meter main reflector) the technique can take days on a single node of a supercomputer. Utilizing the standard technique to compute the noise temperature for all the cases required to properly characterize the SKA design is clearly not feasible. At least a 100 to 1000 speedup in the computation time is required. An approximation technique that can accomplish this improvement with extremely small errors in noise temperature calculation of a few tenths of Kelvin is now described.

The noise temperature contribution from the main beam is primarily given by the brightness temperature in its pointing direction and the spillover from the sub and feed contributes the remainder of the noise temperature. However, computing the main beam over the 4 pi steradians is the major time consuming element since it is the larger of the two reflectors and thus requires a finer integration grid as well as more computed points to capture the pattern variations. However, as only using the feed and subreflector pattern does not suppress the radiation behind the main reflector. The full 4 pi steradians pattern using all field components at 1.4 GHz using the shaped geometry of the type shown in Fig. 4 fed with a Lindgren quad ridge feed is shown in fig. 10 and the radiation pattern using only the feed plus subreflector components is shown in Figure 11. Both patterns are shown over a 50 dB dynamic range referenced to the peak gain. Fig. 12 shows the shadow generated by the rays radiated from the feed that are blocked by the main reflector. Applying the mask of Fig. 12 to the feed plus subreflector pattern of Fig. 11 produces the radiation pattern of Fig. 13. This pattern contains the energy from the main and subreflector diffraction cones but not the main beam itself. Using the radiation pattern from Figure 13 in equation 2 and adding the brightness temperature in the direction of the main beam provides an excellent approximation of the noise temperature without having to calculate the radiation pattern of the main reflector. The computer time is reduced by a factor of 100 to 1000 with the larger savings at the higher frequencies. Fig. 14 compares the approximate technique to an exact noise temperature over a wide frequency range. From this point forward, all the noise temperature results will use the approximate method.

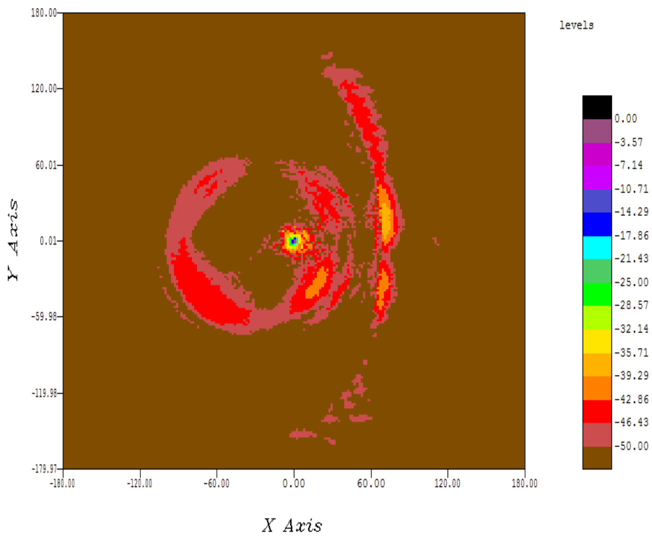

Figure 10. Total Radiation Pattern at 1.4 GHz

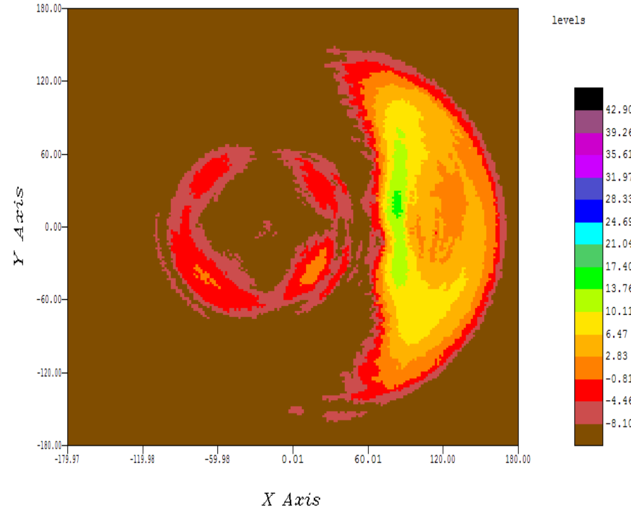

Figure 11 Radiation Pattern with only Feed and Subreflector

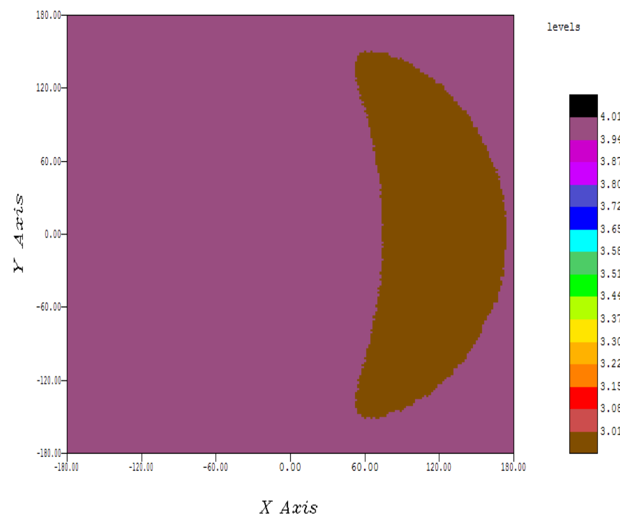

Figure 12 Main reflector blockage mask

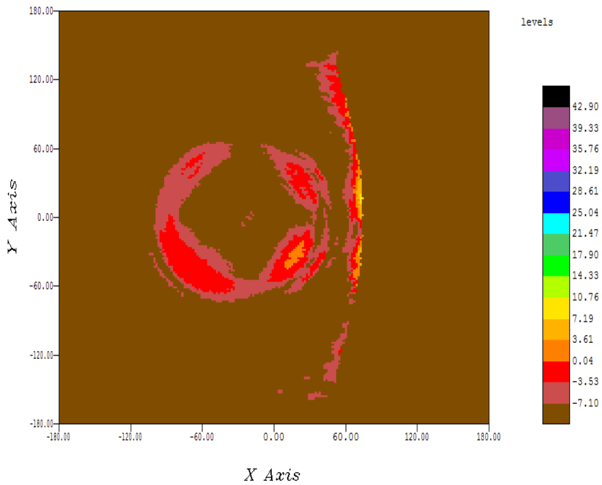

Figure 13 Feed and Subreflector pattern with Mask applied

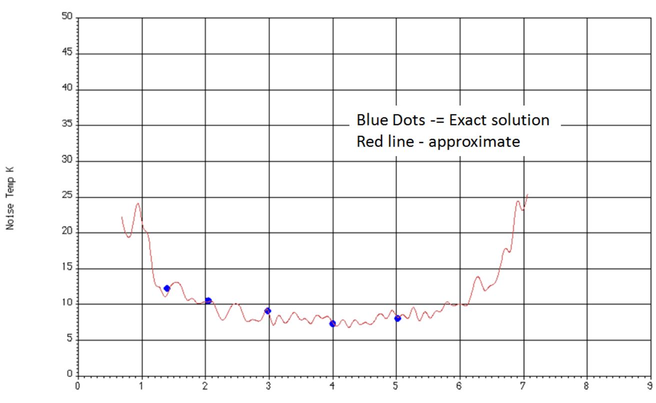

Figure 14. Comparison of approximate and exact computations for Lindgren Shaped Optics with 45 degree opening angle

Noise temperature results for shaped designs

After having made the decision to utilize a shaped design the next important step is to determine the optimum opening angle for each feed that maximizes the G/T or equivalently Ae/Tsys for that feed. Figure 15 shows the noise temperature for the ATA calculated feed. Using the efficiency shown in fig. 7 and assuming a 15K amplifier, a plot of Ae/Tsys is shown in fig. 16. Figure 17 shows Ae/Tsys for the Lindgren feed as a function of frequency and subreflector opening angle. For the Lindgren feed an opening angle between 40 to 45 degrees optimizes the G/T. Figure 18 shows QSC improved feed. For the QSC improved feed an opening angle of 75 degrees was optimum. Larger opening angles create the need for a larger main reflector so, for cost considerations there is a desire to stay away from larger opening angles.

At this point it is obvious that the feed development is at an early stage in that the measured patterns as a function of frequency are not available for all the feeds. However, due to schedule considerations it is imperative to make a choice on the optics design before the feed development is mature. A potential solution is shown in the following section.

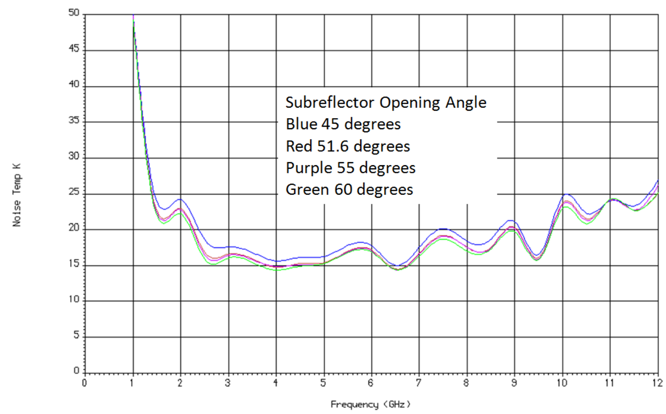

Figure 15. ATA Calculated Feed (Noise Temperature)

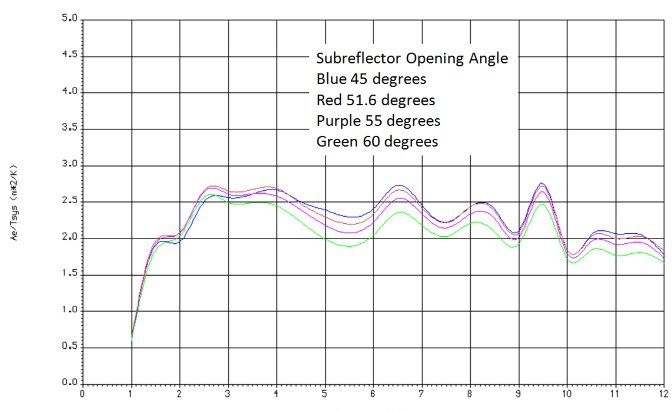

Figure 16. ATA calculated feed (12-meter antenna) Ae/Tsys

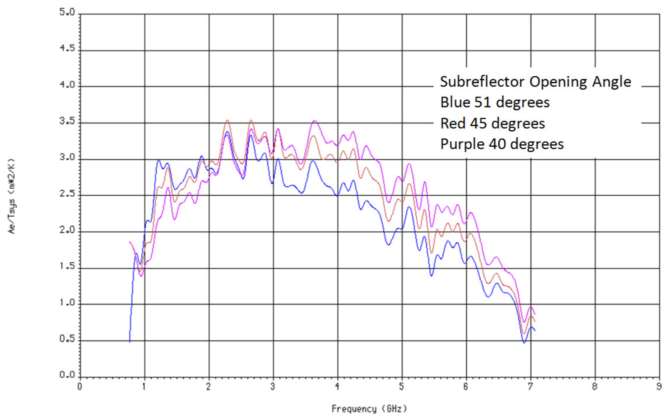

Figure 17. Lindgren Feed (12-meter antenna) Ae/Tsys

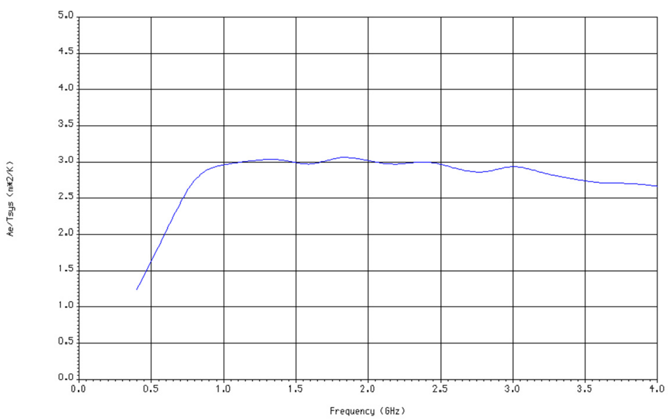

Figure 18. QSC_i feed (12-meter antenna) 75 degree opening angle

6. Variable Shaping to Create New Subreflectors

The choice of feed for the optics is not yet obvious, which makes it difficult to proceed with the final reflector design. It is possible to create new shaped subreflectors matched to a previously designed primary reflector, providing a different opening half angle than the original design. This concept provides a way to move forward with the main optical design and still have options for the opening half angle

The construction method is simple and is illustrated in Fig. 19. The given primary reflector is shown and is from the 50 degree half angle design. A ray from the aperture point A is reflected from the known primary at point P and propagates toward a set of possible secondary points, S. The ray then reflects at the point S to the new focus F. The choice of point S is calculated by requiring a constant path length along the ray, APSF. The location of the new focus and the choice of constant path length are selectable parameters for the calculation. The procedure is repeated for a complete set of rays from aperture, yielding a locus of points defining the new subreflector surface. This construction method ensures that the reflection law is satisfied at the new subreflector.

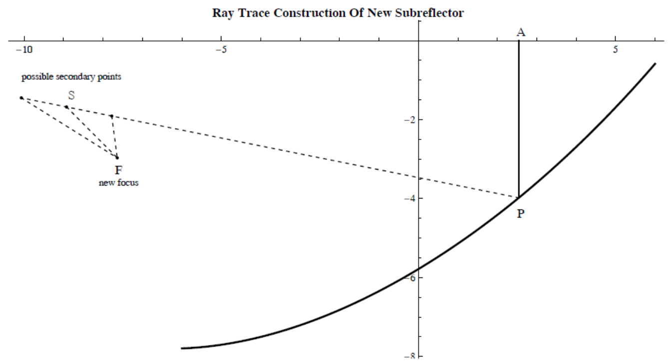

Figure 19. Ray Trace Construction of New Subreflector

Figure 20 shows a cross section of a reflector system calculated with this method and Fig. 21 shows a close up of the new subreflector. The original design had an opening angle of 50 degrees and the new design has an opening angle of 55 degrees. The old subreflector is shown as a dashed line and the old focus is the isolated dot. The new and old subreflectors have the boresight point in common, indirectly selecting the constant path length. Under this choice the only remaining free parameter is the location of the new focus. It is moved in x,z to give the desired new opening half angle with minimum variation in half angle around the rim. Figure 22 shows the opening half angle around the rim for the 32 azimuth values. The variation is very small, yielding an effective design.

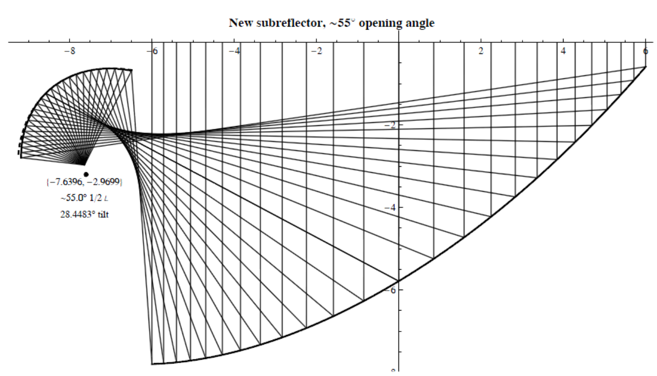

Figure 20. New subreflector, ~55° Opening Angle

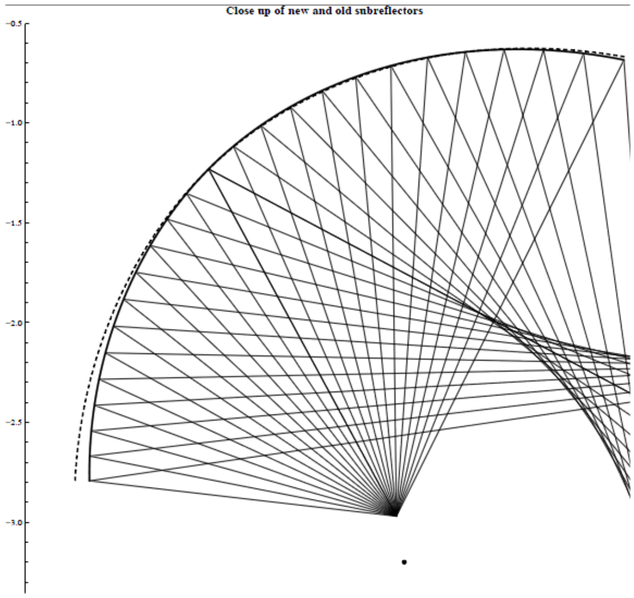

Figure 21. Close up of New and Old Subreflector

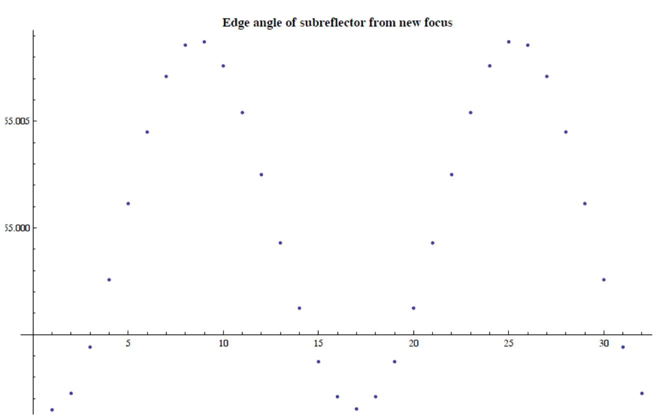

Figure 22. Edge Angle of Subreflector from New Focus

Analysis of four new subreflectors drawn from the 50 degree baseline case at 40, 45, 55, 60 degrees half angle show a very small loss in performance. This technique provides a way to adapt a given primary to different feeds, allowing progress on designing and building the optics while still retaining a wide range of possibilities for the final selection of the feed.

7. CONCLUSION

At this stage of the project the feeds are not mature enough to make a final choice. However the schedule for building the TDP Design Verification Antenna (DVA) requires that a decision on the optics design be made before the feed development is completed. A shaped dual reflector optics design is presented that provides a wide range of subreflector opening angles so the fabrication of the antenna can proceed.

ACKNOWLEDGMENT

Part of the research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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BIOGRAPHY

***William A. Imbriale** received the B.S. degree in engineering physics from Rutgers University, New Brunswick, NJ, in 1964, the M.S. degree in electrical engineering from the University of California, Los Angeles, in 1966, and the Ph.D. degree from the University of Illinois, Urbana-Champaign, in 1969.*

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